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# Environmental Effects of Dredging Technical Notes



## FACTORS INFLUENCING BIOACCUMULATION OF SEDIMENT-ASSOCIATED CONTAMINANTS BY AQUATIC ORGANISMS; FACTORS RELATED TO BIOTA

PURPOSE: This is the third technical note in a series of four which outlines and describes the principal factors that determine uptake and retention of chemicals by aquatic organisms. The first three notes in the series describe factors relating to contaminants, sediment and water, and biota. The fourth note is a glossary and bibliography. The information contained herein is intended to assist Corps of Engineers environmental personnel in activities requiring a working knowledge of concepts and terminology in the subject of chemical uptake, retention, and elimination by aquatic organisms exposed to contaminated sediments.

BACKGROUND: Bioaccumulation is the general term used to refer to the uptake and storage of chemicals by organisms from their environment through all routes of entry. Bioaccumulation includes bioconcentration, which is the direct uptake of chemicals from water alone, and is distinguished from biomagnification, which is the increase in chemical residues taken up through two or more levels of a food chain. Assessments of the potential for bioaccumulation of toxic substances associated with dredged sediments are often required in evaluations of permit requests. Thus, familiarity with the fundamental physical, biological, and chemical factors affecting bioaccumulation is necessary for performing evaluations of the ecological impacts of dredging operations. Additionally, a basic understanding of the concepts and terminology of bioaccumulation is increasingly required of environmental personnel who are involved in dredging and disposal operations which may involve contaminated sediments and legal personnel involved with regulation and litigation.

These notes are intended to serve as a source of basic information and to provide a guide to the scientific literature for each topic discussed. The emphasis is on factors affecting bioaccumulation of sediment-associated chemicals. A brief discussion of each factor is given and a list of references is provided. The references are extensive and frequently bear on more than one topic. An effort has been made to select both historically important works and the most recent research reports in each area. Numbers in parentheses following the subject headings locate the references for each subject. Papers referenced are alphabetized for each subject for easy identification of those most pertinent to the reader's interest. The glossary of technical terminology is presented in the fourth note in the series.



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The subjects discussed in these notes reflect current research for which new findings constantly appear in the literature. Consequently, the discussions and interpretations are based on inference and best judgement regarding the interactions of factors influencing bioaccumulation and represent the best understandings of the authors. Readers are encouraged to consult the literature cited.

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## Biotransformation (138-148)

Biotransformation is the process by which foreign chemical substances are enzymatically oxidized, reduced, cleaved, rearranged, or conjugated within the metabolically active organs of biota. In Phase I of metabolic detoxication, foreign chemical compounds are biotransformed to reactive metabolites (bioactivation) enabling them to undergo further chemical reactions. Bioactivation is usually followed by conjugation with endogenous substrates in Phase II of metabolic detoxication, and excretion from the organism. Biotransformation can also result in activation of a foreign compound to a toxicant of higher potency than the parent compound, as is the case with the polynuclear aromatic hydrocarbon (PAH) benzo[a]pyrene. There are substantial differences among organisms in their ability to biotransform chemicals. For example, the PAHs tend to bioaccumulate in certain amphipods and bivalves that do not possess the enzyme systems necessary to metabolically detoxify and eliminate them. These same PAHs are found in much lower concentrations in most fishes because the fishes do possess the necessary enzyme systems for biotransformation and degradation.

The effect of biotransformation is to reduce the amount of unchanged chemical that is bioaccumulated by an organism. However, in some cases, metabolites may be bioaccumulated rather than excreted. For example, dichloro-diphenyl-trichoroethane (DDT) is metabolized to the -dichloroethane (DDD) and then to the -dichloroethylene (DDE) by most aquatic organisms. Over time DDT residues in organisms diminish, while DDE residues increase.

## Depuration (149-155)

Depuration refers to the elimination of toxic substances from an aquatic organism by all processes and occurs concomitantly with uptake of chemicals. Steady-state bioaccumulation is considered to exist when the net loss of a chemical by depuration is equal to the net gain by uptake. Removal of an organism to conditions of lower exposure favors depuration over uptake. In most cases, depuration is a biphasic process; first, chemicals in the bloodstream or in tissues with high blood-exchange are depurated, and then the same chemicals in storage tissues such as depot fat are mobilized and eliminated over a longer period of time.

## Diet (56, 93, 156-166)

Recent studies assign a greater role to contaminated food as a major pathway for bioaccumulation of contaminants in aquatic organisms. High levels of chemicals in the tissues of water column-dwelling fishes that are exposed to only very low concentrations of chemicals in the water are explained on the basis of ingestion of contaminated food. Benthic infaunal species that ingest sediment as a part of their diet probably also receive a large part of their body burden through feeding. Dietary accumulation is dependent on feeding and clearance rates and on the ability of organisms to assimilate chemicals. If the food that an organism ingests is highly contaminated relative to the water that the organism respires, and if the quantity of contaminated food ingested is also large, diet is likely to be the dominant pathway for bioaccumulation.

## Feeding Type (167-169)

Bioaccumulation through dietary exposure is also influenced by the manner in which an organism obtains its food, i.e., the organism feeding type. The assimilation efficiency of organic chemicals and organometalloids from food to predatory fish ranges about 65-95 percent. Deposit feeders that ingest contaminated sediment assimilate these contaminants with about 20-40 percent efficiency. Filter feeders are intermediate or similar to deposit feeders in their assimilation efficiencies.

## Kinetics of Uptake and Elimination (81, 141, 153, 170-196)

The rates at which chemicals are taken up and eliminated by organisms are major determinants of both the time required for and the magnitude of bioaccumulation. Bioaccumulation in aquatic organisms is most commonly viewed as a one-compartment model in which uptake and elimination take place simultaneously, but at different rates. Rate constants for uptake ($k_1$) and for elimination ($k_2$) can be calculated from empirical data or can be estimated from physiocochemical parameters such as $K_{ow}$. The ratio, $K_1/K_2$, is the bioconcentration factor (BCF) of a chemical when the exposure medium is water. The same model has been applied to contaminants in sediments, in which case $k_1/k_2$ is the sediment bioaccumulation factor (BAF) and relates chemical concentration in sediment to steady-state concentration in exposed organisms. A fundamental requirement of the simple kinetic model is that exposure concentration be constant. At constant exposure, the concentration of chemical in the tissues of an organism at steady state exceeds the concentration in the exposure medium by the magnitude of the BCF (or BAF). Although steady-state conditions rarely occur in the real world, the concept is a useful simplification that makes kinetic calculations possible.

For nonmetabolizing neutral organic chemicals, the rate of elimination is inversely correlated with hydrophobicity, resulting in very slow elimination for the higher molecular weight hydrophobic compounds. However, rates of uptake for such chemicals are generally rapid. Such compounds are taken up and eliminated passively, and bioaccumulation usually follows first-order kinetics as described above. The slower the rate of elimination, the greater will be the magnitude of bioaccumulation for a given chemical. For chemicals that are metabolized, rates of elimination can be accelerated by mixed-function oxidase (MFO) induction (see "Mixed-Function Oxidases"). Animals receiving prior exposure to the same or to similar chemical substances may develop the ability to depurate those substances rapidly by having synthesized greater quantities of MFOs. Bioaccumulation under these circumstances is reduced compared to bioaccumulation in similar but chemically naive animals.

In a few studies first-order kinetics have also been able to describe the uptake and elimination kinetics of metals. However, the kinetics of metal bioaccumulation are influenced by many more variables than are the kinetics of

hydrophobic organics, and simple models are generally less successful in describing them.

## Lipid Content (87-88, 171, 197-205)

Hydrophobic chemicals tend to be stored in body lipids, predominantly in fat. Lipids are organic substances of biological origin that are insoluble in water. Lipids include structural substances such as phosphatides, substances that are involved in various biochemical reactions such as steroids and carotenoids, and the fats and waxes. Fats are relatively inert substances that constitute reserve energy stores for biota. Storage lipids composed primarily of fats have the highest affinity for neutral chemicals. In general, the higher the total lipid content of an organism, the greater its capacity for bioaccumulation of hydrophobic chemicals. The total lipid content of an aquatic organism or the lipid content of specific tissues is now frequently used as a basis for normalizing the concentration of neutral organic chemicals found in organisms. Normalization of concentration data makes it possible to make interspecies comparisons of bioaccumulation. Analytical procedures for lipids in biota have not yet been standardized for environmental samples. Total lipids are often measured gravimetrically as the residue after evaporation of a hexane extract prepared for analysis of organic contaminants in aquatic biota.

## Metabolic Rate (14, 145, 150, 156, 176, 194, 206-211)

Metabolic rate affects bioaccumulation in several ways. A high rate of metabolism is usually accompanied by increased rates of oxygen uptake. Rates of oxygen uptake closely parallel rates of contaminant uptake from water in aquatic species. However, rates of biotransformation and excretion may also be accelerated by increases in metabolic rate. The net effect on bioaccumulation depends on whether the uptake or depuration process is favored. For example, elevated metabolic rate during a period of reduced external contamination in most cases would tend to favor increased elimination of chemicals and a reduction in body burden.

## Metallothioneins (212-222)

Low molecular weight sulfur-containing proteins that bind certain metals (metallothioneins) are produced in the kidneys, livers, gills, and digestive organs of most aquatic organisms. Metallothioneins primarily are involved with regulating the metabolism of essential trace metals. However, for many organisms metallothioneins also provide a measure of protection against the toxic effects of certain metals, mainly Cu, Cd, Zn, and Hg. The synthesis of metallothioneins is inducible in a manner analogous to MFO induction. Low-level acute or chronic exposure of biota to certain metal ions can produce a tolerance to the toxic effects of those metals through the induction of metallothioneins. The consequence of metallothionein induction to bioaccumulation is an enhanced ability of organisms to accumulate certain metals before the appearance of toxic effects.

## Mixed-Function Oxidases (138, 140, 147, 223-235)

Mixed-function oxidases (MFOs), also referred to as monooxygenases, are cytochrome P-450-dependent intracellular enzymes that function mainly in the oxidative metabolism of lipoidal endogenous compounds such as steroids, and in the first phase of detoxication of foreign organic compounds. Several types of MFOs may be found in metabolically active organs of all vertebrates, including fishes, and of most invertebrates. In fishes and aquatic invertebrates, the most highly developed MFO systems are those that catalyze the biotransformation of planar aromatic lipid-soluble chemicals like the PAHs into more water-soluble compounds. Increasing the water solubility of such compounds makes them more easily eliminated. Exposure of an inducible organism to low PAH concentrations or to sufficiently similar compounds, such as the coplanar polychlorinated biphenyls (PCBs), stimulates (induces) the synthesis of appropriate MFOs for detoxication of those compounds. Subsequent exposure of the induced organism to the same or to a chemically similar organic chemical can be met with an increased capacity to eliminate the chemical and a reduced level of bioaccumulation.